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Interprovincial transfer of embodied primary energy in China: A complex network approach

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HIGHLIGHTS

- A network model is constructed by integrating EEBT and network theory.
- China's multi-layer primary energy flow is tracked at the provincial level.
- Different potential drivers are identified for four types of energy flow.

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ABSTRACT

The energy supply–demand security and climate change has continued to be problematic, making it significant and necessary to investigate embodied energy flow, particularly in a large and fast-growing developing country like China. One of the effective approaches is the energy/emissions embodied in bilateral trade (EEBT) aiming to locate the destination of energy bi-directionally to evaluate how energy flow between producer and consumer sectors. However, in addition to the flow of energy and resources, the topological structure and impact of underlying components from a system science perspective are equally important for policy-making. This study therefore constructs an energy embodied in trade network (EETN) model to track multi-layer primary energy flow by integrating the EEBT approach and complex network analysis. The embodied coal, oil, natural gas, and non-fossil fuels associated with China's 30 provinces/municipalities are quantified at the provincial level. By the joint analysis of the network-oriented metrics, the EETN model elicits the possibility of understanding the heterogeneity distribution of different types of energy flow and the potential impact of province-specific policy interventions. We explain how resource endowment, economic growth, income inequality, cross-provincial industrial transfer, and infrastructures affect China's provincial energy embodiments as well as the clustering features. Other findings and policy recommendations are also presented.

1. Introduction

From 1971 to 2014, the world total primary energy supply (TPES) increased almost 2.5 times. In 2014, the TPES reached 13,700 Mtoe, releasing over 32 GtCO_2 [1,2]. Fossil resources accounted for almost 82% of global energy production. As stated by Hall, non-renewable fossil fuels have been inextricably linked to the economic process as well as the potential limits to growth of modern societies [3]. The security of energy supply and emission of pollutants/greenhouse gases are the main concerns relating to fossil fuel depletion, and are addressed by political initiatives and research efforts in many countries, such as India [4], China [5], and Iran [6]. In global discussions aimed at limiting carbon emissions, the national targets are tied to energy use generated within national borders. Ultimately, the key to reducing carbon intensity lies in optimizing the energy fuel mix and improving energy efficiency.

As a major contributor, China accounted for nearly 22% (3,052 Mtoe) of TPES. Under these circumstances, China has committed to reducing its carbon intensity by 60% to 65% by 2030 from the 2005 level, peaking its carbon emissions, and increasing non-fossil fuels to 20% of its energy mix. China's 13th Five-Year Plan (2016 to 2020) for energy stipulates that China will control an aggregated emission reduction, ecological environment quality, and efficiency of energy resource usage.

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Nomenclature

EEBT	energy/emissions embodied in bilateral trade
EETN	energy embodied in trade network
TPES	total primary energy supply
I-O	input-output
MRIO	multi-regional input-output
HEET	hybrid emissions embodied in trade
WIOD	world input-output database
ROW	rest-of-world
GDP	gross domestic product
LNG	liquefied natural gas
EKC	environmental Kuznets curve
MYE	middle reaches of the Yellow River
MYA	middle reaches of the Yangtze River
Mtoe	million tons of oil equivalent
$GtCO_2$	gigatonnes of carbon dioxide
TJ	terajoule
PJ	petajoule
USD	USA dollar
KW	kilowatts
kWh	kilowatt hour
NE	northeast
NC	north coast
EC	east coast
SC	south coast
NW	northwest
SW	southwest
SWD-EET	step-wise distribution of emissions embodied in trade
TIIOT	Transnational Interregional Input-Output Table
DRC	Development Research Center of the State Council of the People's Republic of China

However, China's interprovincial product trade is becoming increasingly frequent because of multiple factors, such as resource endowment, industrial structure, and level of economic development. Product trade results in the transfer of energy consumption (the so-called embodied energy). Thus, one province can reduce its local energy use by directly importing products from other provinces or by reducing the export of high-energy consuming products.

In particular, the contradiction between the energy supplier and receiver presents challenges, which leads to limited optimization configuration of clean energy across the country together with increasing risks in interprovincial channels. The effective adjustment of the relationship between local energy balance and cross-provincial supply promises to address these challenges, as well as ultimately enabling the entire decarbonization of China's interprovincial energy supply [7].

Therefore, more reasonable energy saving and trade adjustment measures between provinces will benefit the realization of national targets. The first task is to fully grasp the characteristics and potential drivers of interprovincial energy transfer from a systems view. The contributions of this paper include (a) combine the global input-output tables and China's interregional input-output tables to investigate the embodied energy flows at the regional level by different energy types; (b) combine the embodied energy flows analysis with the complex network approach to identify the structure of the regional embodied energy flow network; (c) use the community concept to reveal the driving forces involved in the interwoven embodied energy flows.

The remainder of this paper is organized as follows: in Section 2, a detailed literature review is provided. Section 3 of the paper explains the estimation of energy embodied in trade using a multi-regional input-output framework and constructs the energy embodied in trade network using complex network theory. The empirical results of the constructed network are presented in Section 4. The final section summarizes the paper's main findings and future prospects.

2. Literature review

With the magnitude of potential energy consumption, research into embodied energy has been a lively topic. Abundant examples can be found in recent literature that has been applied to different subjects. For example, Liu et al. explored energy use from all industrial sectors in China and found that total indirect energy consumption accounted for 80.6% of total embodied energy consumption [8]. Yang and Chen evaluated the embodied energy of a wind power generation system. The results showed that wind power is more competitive in terms of energy savings compared with other power generation systems [9]. Miró et al. accounted for embodied energy in terms of the total energy inputs of thermal energy storage complementing solar plants [10]. Wu et al. established a complete inventory of energy inputs in a typical coal-power plant and considered the energy embodied in materials, equipment, and services [11]. Most of these studies have focused on the energy directly and indirectly used for the production and delivery of goods or services along their whole life cycle. To reduce the energy consumption of China's building sector, Zhang and Wang used the hybrid input-output approach to analyze supply-chain energy by dividing the life cycle into construction, operation, and disposal stages, finding that energy in the disposal stage contributes significantly to the impact of the overall life cycle [12].

In addition, embodied energy transfer is also a part of the normal pattern of economic phenomena occurring through international trade. Some scholars have studied the energy embodied in trade for a certain country or the main economies in the world. Machado et al., for example, evaluated the total impact of international trade on Brazil's energy use and suggested that the extra influence of international trade policy to be of concern [13]. Cortés-Borda et al. quantified the amount of solar energy embodied in trade between 10 economies [14]. In the existing literature, input-output (I-O) analysis is widely recognized as the appropriate methodological tool to perform energy embodiment analysis. Wiedmann et al. demonstrated that there is no "best" model, but only a "best" model for a specific purpose. I-O analysis is very detailed in its description of commodities produced in economies and can provide detailed static ex-post accounting tools for monetary and non-monetary (physical) quantities [15]. Rocco and Colombo evaluated the energy embodied in national products through I-O analysis and suggested that the use of appropriate international trade treatment methods is needed [16]. Since the I-O tables capture the exact quantitative economic relationships between industrial sectors, scholars have carried out large numbers of I-O analyses regarding the energy embodied in trade. See, for example, the review of methods in Sato [17] and the survey of the empirical literature studying embodiments in China's foreign trade in Zhang et al. [18].

The above studies provide two main environmentally extended I-O models to study the energy embodied in multi-national trade: the multi-regional input-output approach (MRIO) and energy/emissions embodied in bilateral trade approach (EEBT) [19]. MRIO considers trade to final consumption and endogenously determined trade to intermediate consumption. For example, Wiedmann compared energy footprints embodied in trade in the UK in 2002, and concluded that MRIO models will be particularly suitable to estimate the ecological footprints of national trade and to track their origin via inter-industry linkages, international supply chains, and multi-national trade flows [20]. Sato et al. used an MRIO model to estimate the quantities and directions of embodied energy flows in the global supply chains of 134 countries, and evaluated the diversity of the embodied-energy trade [21]. The new approach of the MRIO model to alleviate energy embodied in the commodity trading process leads to more people being concerned with this issue. EEBT focuses more on the domestic supply chain and

incorporates the total trade (intermediate and final consumption) between bilateral trading partners. It captures the share of domestic emissions from the exported products of bilateral partners, a method that is considered an advantage over MRIO because the MRIO method only allocates emissions to the country of final consumption [22]. However, most of the studies that focused on EEBT method were mainly used in the field of emissions rather than energy embodiment. For example, Kanemoto et al. compared the EEBT method (which considers total trade flows with domestic emission intensities) with the MRIO method (which considers trade only into final consumption with global emission intensities), and suggested using an EEBT approach if trade-adjusted emission inventories were to be compared [23]. Wu et al. estimated the embodied CO_2 emission flows between China and Japan using the EEBT approach [24].

However, these studies only considered their work from a global and national perspective, ignoring regional disparities within a country. Only a very few studies have been conducted in the context of regional economy, especially for a large country such as China, because data limitations is always a challenge in empirical studies. Some scholars divided Chinese provinces into different regions to explain embodied energy/emissions distribution and absorption patterns through interregional trade, and compared developed with developing regions. For example, Su and Ang combined the hybrid emissions embodied in trade (HEET) approach and step-wise distribution of emissions embodied in trade (SWD-EET) analysis to explain how interregional trade and international trade affect China's regional domestic emissions [25]. Zhang et al. investigated the temporal and spatial changes of embodied energy transfers via China's domestic trade for 2002–2007 based on MRIO models [26]. Hong et al. employed an MRIO model to investigate energy use embodied in the consumption and interregional trade of China's construction industry in 2007 [27]. Some have focused on part of China's provinces/municipalities – the Jing-Jin-Ji area [28] and Beijing-Tianjin-Shanghai-Chongqing municipalities for instance [29].

Only a few studies have examined the potential driving factors of embodied energy flows; such drivers as fuel switching, energy efficiency, supply, and consumption structure are widely studied in emissions research. For instance, Su et al. investigated the driving forces of Singapore's household-related emission changes using I-O analysis and structural decomposition analysis [30]. Zhang et al. investigated the socioeconomic determinants affecting mercury emissions combined with emission linkage analysis and structural decomposition analysis [31]. Gasim examined the role of specialization in driving embodied energy and emissions trade patterns by conducting a spatial index decomposition analysis of embodied energy for 41 economies, and revealed that specialization makes the biggest contribution while energy intensity and the trade balance make an equally important contribution [32].

Real embodied energy transfer is a complex system with numerous regions and complicated relationships. The development of complex network theory has offered an effective tool for studying international energy trade. For example, Gao et al. built a multilayer network of international fossil energy trade and studied its evolutionary characteristics using complex network theory [33]. Duan and Chen analyzed the energy-water nexus embodied in international energy trade via a combination of I-O analysis and ecological network analysis [34]. The usefulness of this approach also has been proven by many studies of embodied energy. For example, Vora et al. presented a network model to study the embodied irrigation energy traded by food across the US in 2012 [35]. Shi et al. applied complex network theory to study the sensitivity, key sectors, and clustering features of global embodied energy flow [36]. Chen et al. studied the structure of embodied energy flow at global, regional and national level based on environmentally extended I-O analysis and complex network analysis [37]. These studies mainly focus on recent years which illustrates that the theory of complex network is becoming a hot and effective method for energy system research.

The present study uses complex network theory to reveal the characteristics or rules of completed energy flows embodied in China's interprovincial trade, such as key provinces and clustering features, and further explore the underlying drivers behind the embodied energy flows. A comprehensive study of primary energy embodiments, including coal, oil, natural gas, and non-fossil fuels, is presented. No embodied energy/emission studies have been carried out to identify the potential drivers of embodiment flows by different energy types at the global, national, and provincial level. Two main lines of enquiry are depicted in this study. One is the scope of research: global → China → Chinese provinces. In the calculation of embodied energy inflows and outflows between China's provinces, international import and export cannot be ignored. Thus, a global perspective should be adopted in which all economies are included. The other refers to research objects: provinces → transfer links → underlying drivers. For the realization of China's energy saving and emission reduction targets, it is extremely important to identify the dominant provinces producing, consuming, importing, or exporting large amounts of energy. The potential drivers of clustering features are measured and discussed according to the intricate relationships involved in embodied energy flows between provinces, which will provide future reference for China's regional and national energy consumption reduction.

3. Data and methodology

3.1. Data

The 2009 world I-O table was taken from the world input-output database (WIOD) [38]. This is an important database for I-O researchers. For WIOD data, we used basic-price industry-by-industry I-O data for the world economy, which covers 41 major countries/regions. It offers a complete set of world I-O tables providing the monetary flow between 1435 sectors, including 35 sectors for 27 European Union countries, 13 other major countries and an aggregation of all the remaining countries into a single region labeled rest-of-world (ROW). We chose the 2009 annual data because the energy use data is only available during 1995–2009 [38]. For example, recent publication by Jiang and Guan also used the latest WIOD dataset up to year 2009 to study the drivers to global CO_2 emissions growth [39]. White et al. only used the latest 2005 Transnational Interregional Input-Output Table (TIIOT) data together with the information taken from the WIOD database to study the water-energy-food nexus in East Asia [40]. Our investigation includes the several energy types: coal, oil, natural gas, and non-fossil fuels (unit in TJ). To avoid double-counting, only primary energy was analyzed by removing electrical energy. Thus, this study covers all forms of primary energy sources.

We use the 30-province/municipality data for China to illustrate the constructed network; this will be discussed in the following sections. The main I-O data source is the China Regional Input-Output Tables 2010 [41]. For each province, the I-O table contains 42 sectors. The multi-regional I-O data in 2009 can be then obtained by the China Regional Input-Output Tables 2010 and the gross domestic product (GDP) data. The provincial GDP data was collected from the National Bureau of Statistics of China [42]. The data treatment scheme proposed in Ref. [43] was used to disaggregate the energy data to match the detailed I-O classifications to ensure comparability. The detailed technique can be found in Su and Ang [43].

The revised I-O table outlined in Table 1 was estimated using the same scheme proposed in Ref. [43], compiled based on the Chinese 30-province I-O tables and international trade matrices (units in USD). As a result, we divided the world economy into 71 regions, i.e. 30 provinces/municipalities in Mainland China, 40 world economies (excluding China) and ROW.[1] We combined these into a 20-sector table without excluding important information, because the sector classifications of

[1] The list of country follows WIOD by inserting South Africa behind the USA. The ranking of China in the original multi-regional I-O table is 7. Thus, the rankings of China's 30 provinces in Table 1 range from 7 to 36.

Table 1
Revised multi-regional I-O table.

Input		Output: Intermediate use: Australia (R1) Sector 1 ⋯ Sector 20	⋯	ROW (R71) Sector 1 ⋯ Sector 20	Final use: Australia (R1) ⋯ ROW (R71)	Total output
Australia (R1)	Sector 1 ⋮ Sector 20	z_{ij}^{sr}			y_i^{sr}	x_i^s
⋮	⋮					
Beijing (R7)	Sector 1 ⋮ Sector 20					
⋮	⋮					
Xinjiang (R36)	Sector 1 ⋮ Sector 20					
⋮	⋮					
ROW (R71)	Sector 1 ⋮ Sector 20					
Direct primary energy input	Coal Oil Natural gas Non-fossil fuels	d_i^s				

basic I-O tables are not identical with those of energy balance sheets. The sectors are listed in Table A1 in Appendix A.

3.2. Calculation of energy embodied in trade

The coordination of flow of goods and direct primary energy input is illustrated in Table 1. The multi-regional I-O table shows intermediate use represented by z_{ij}^{sr}, which reflects the capital movement of goods from sector i in country s to sector j in country r; final use is represented by y_i^{sr}. In the production process, each sector in all countries consumes direct energy represented by d_i^s (unit in TJ). With international trade, goods flow from one sector of a country to the sectors in other countries. Meanwhile, the primary energy (including coal, oil, natural gas, and non-fossil fuels) embodied in goods transfers from one country to another.

On the basis of the concept of embodied energy originating from the theory of systems ecology, the total energy input to satisfy final demand (i.e., the direct plus indirect energy resources input through the production processes to produce the goods used for final demand) is termed the 'embodied energy requirement' [44]. Fig. 1 shows the balance of embodied energy for sector i in region s, where d_i^s represents the direct energy input for sector i in region s; ε_j^r and ε_i^s represent the direct energy intensity of sector j in region r and sector i in region s respectively; z_{ji}^{rs} represents the intermediate input from sector j in region r to sector i in region s; and y_i^{sr} represents the sum of the final consumption for sector i in region r. Therefore, the embodied energy balance for sector i in region s can be formulated as:

$$d_i^s + \sum_r \sum_j (\varepsilon_j^r \times z_{ji}^{rs}) = \sum_r \sum_j \varepsilon_i^s (z_{ij}^{sr} + y_i^{sr}) \tag{1}$$

Thus, the entire I-O table can be expressed in the matrix equation:

$$\boldsymbol{D} + \boldsymbol{Z}^T \times \boldsymbol{E} = \boldsymbol{X} \times \boldsymbol{E} \tag{2}$$

where
$$\boldsymbol{Z} = \begin{bmatrix} \boldsymbol{Z}^{1,1} & \cdots & \boldsymbol{Z}^{1,71} \\ \vdots & \ddots & \vdots \\ \boldsymbol{Z}^{71,1} & \cdots & \boldsymbol{Z}^{71,71} \end{bmatrix} = \begin{bmatrix} \begin{pmatrix} z_{1,1}^{1,1} & \cdots & z_{1,20}^{1,1} \\ \vdots & & \vdots \\ z_{20,1}^{1,1} & \cdots & z_{20,20}^{1,1} \end{pmatrix} & \cdots & \begin{pmatrix} z_{1,1}^{1,71} & \cdots & z_{1,20}^{1,71} \\ \vdots & & \vdots \\ z_{20,1}^{1,71} & \cdots & z_{20,20}^{1,71} \end{pmatrix} \\ \vdots & \ddots & \vdots \\ \begin{pmatrix} z_{1,1}^{71,1} & \cdots & z_{1,1}^{71,1} \\ \vdots & & \vdots \\ z_{20,1}^{71,1} & \cdots & z_{20,20}^{71,1} \end{pmatrix} & \cdots & \begin{pmatrix} z_{1,1}^{71,71} & \cdots & z_{1,1}^{71,71} \\ \vdots & & \vdots \\ z_{20,1}^{71,71} & \cdots & z_{20,20}^{71,71} \end{pmatrix} \end{bmatrix},$$

$$\boldsymbol{E} = \begin{bmatrix} \boldsymbol{E}^1 \\ \vdots \\ \boldsymbol{E}^{71} \end{bmatrix} = \begin{bmatrix} \begin{pmatrix} \varepsilon_1^1 \\ \vdots \\ \varepsilon_{20}^1 \end{pmatrix} \\ \vdots \\ \begin{pmatrix} \varepsilon_1^{71} \\ \vdots \\ \varepsilon_{20}^{71} \end{pmatrix} \end{bmatrix}, \quad \boldsymbol{D} = \begin{bmatrix} \boldsymbol{D}^1 \\ \vdots \\ \boldsymbol{D}^{71} \end{bmatrix} = \begin{bmatrix} \begin{pmatrix} d_1^1 \\ \vdots \\ d_{20}^1 \end{pmatrix} \\ \vdots \\ \begin{pmatrix} d_1^{71} \\ \vdots \\ d_{20}^{71} \end{pmatrix} \end{bmatrix}, \quad \text{and}$$

$$X = \begin{bmatrix} \sum_r (\boldsymbol{Z}^{1,r} + \boldsymbol{Y}^{1,1}) & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \sum_r \boldsymbol{Z}^{71,r} + \boldsymbol{Y}^{1,71} \end{bmatrix}$$
$$= \begin{bmatrix} \begin{pmatrix} \sum_{k=1}^{71} \sum_{j=1}^{20} z_{1,j}^{1,k} + \sum_{k=1}^{71} y_1^{1,k} \\ \ddots \\ \sum_{k=1}^{71} \sum_{j=1}^{20} z_{20,j}^{1,k} + \sum_{k=1}^{71} y_{20}^{1,k} \end{pmatrix} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \begin{pmatrix} \sum_{k=1}^{71} \sum_{j=1}^{20} z_{71,j}^{71,k} + \sum_{k=1}^{71} y_1^{71,k} \\ \ddots \\ \sum_{k=1}^{71} \sum_{j=1}^{20} z_{71,j}^{71,k} + \sum_{k=1}^{71} y_{20}^{71,k} \end{pmatrix} \end{bmatrix}$$

By transforming Eq. (2), the embodied energy intensity vector $\boldsymbol{E}$ can be obtained as Eq. (3) because $(\boldsymbol{X}–\boldsymbol{Z}^T)$ is reversible due to the construction standard of the economic input-output table.

$$\boldsymbol{E} = (\boldsymbol{X}–\boldsymbol{Z}^T)^{-1} \times \boldsymbol{D} \tag{3}$$

Therefore, the embodied energy flow $\boldsymbol{F}$ between regions by sectors can be calculated using a EEBT model as:

$$\boldsymbol{F} = \begin{bmatrix} \boldsymbol{F}^{1,1} & \boldsymbol{F}^{1,2} & \cdots & \boldsymbol{F}^{1,71} \\ \boldsymbol{F}^{2,1} & \boldsymbol{F}^{2,2} & \cdots & \boldsymbol{F}^{2,71} \\ \vdots & \vdots & \ddots & \vdots \\ \boldsymbol{F}^{71,1} & \boldsymbol{F}^{71,2} & \cdots & \boldsymbol{F}^{71,71} \end{bmatrix}_{(20\times71)\times(20\times71)} \tag{4}$$

where $\boldsymbol{F}$ represents the block-$\boldsymbol{F}^{sr}$ matrix of size 1420 × 1420 with element f_{ij}^{sr}.

The domestic energy demand in domestic production in region s can be calculated using:

$$\boldsymbol{F}^{ss} = diag(\boldsymbol{E}^s) \times (\boldsymbol{I}–\boldsymbol{A}^{ss})^{-1} \times diag(\boldsymbol{Y}^{ss}), \quad s = 1,2,...,71 \tag{5}$$

The energy use embodied in trade from region s to region r can be calculated using:

$$\boldsymbol{F}^{sr} = diag(\boldsymbol{E}^s) \times (\boldsymbol{I}–\boldsymbol{A}^{ss})^{-1} \times diag(\boldsymbol{e}^{sr}), \quad r = 1,2,...,71 \tag{6}$$

where $\boldsymbol{F}^{ss}$ represents the domestic energy demand in domestic production of region s. $\boldsymbol{F}^{sr}$ is the embodied energy exporting from s to r. $\boldsymbol{E}^s$ is a diagonalised vector of industry-specific energy intensities. $\boldsymbol{I}$ is the identity matrix. $\boldsymbol{A}^{ss}$ is the coefficient matrix of region s's intermediate

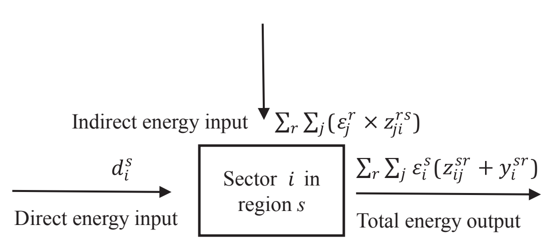

Fig. 1. The principle of balance of embodied energy for sector i in region s.

input. The matrix $(\boldsymbol{I}-\boldsymbol{A}^{ss})^{-1}$ is called the 'Leontief Inverse matrix'. $\boldsymbol{Y}^{ss}$ is the final consumption produced domestically and $\boldsymbol{e}^{sr}$ is the intermediate and final demand of region r produced by region s. All matrices in Eqs. (5) and (6) are of size 20 × 20. For more information on the EEBT approach, see Peters and Kirsten [19,45].

3.3. Construction of EETN

Next, using the embodied energy flow matrix calculated by Eqs. (4)–(6), we construct the energy embodied in trade network (EETN) by summing all 20 sectoral flows between any two regions (labeled by $f'^{sr} = \sum_i \sum_j f_{ij}^{sr}$). The EETN is a directed weighted network that can be represented by the set:

$$G = \{V,E\} \tag{7}$$

where G represents the network in 2009, the nodes set $V = \{v_i, i = 1,2,...71\}$ represents 71 countries/regions in the world, and the edges set $E = \{e_{ij}\}$ represents the embodied energy flow between regions. If $f'^{sr} > 0$, then $e_{ij} = 1$ and its weight $w_{ij} = f'^{sr}$; otherwise $e_{ij} = 0$.

According to the principles mentioned above, Fig. 2 provides a description of the research process and integration of analytical tools.

3.4. Indicators for analyzing the EETN

Three main indicators are used to describe the constructed energy flow network: node strength, cumulative distribution of the weights, and community structure.

3.4.1. Node strength

The problem of identifying whether the nodes play a core role is one of the main topics in the traditional analysis of networks, and one of the indicative measurements is the degree of nodes. However, the network of EETN is a nearly complete graph. The analysis of node strength w_i, which generalizes the concept of node degree to the weighted network, tends to be more meaningful. Since the network is directed, each node has both an in-strength $w_{i,in}$ and an out-strength $w_{i,out}$, defined as the sum of the in-flows and out-flows incident to the node. The difference in trade intensity leads to each region having an inconsistent impact, and this paper takes the weighted degree (namely node strength) into account to cater for it as in Eq. (8).

$$w_i = w_{i,in} + w_{i,out} = \sum_j f'^{ij} + \sum_j f'^{ji} \tag{8}$$

where $w_{i,in}$ and $w_{i,out}$ represent the in-strength and out-strength of a node, and f'^{ij} denotes the embodied energy volume from node i to j.

3.4.2. The cumulative distribution of the weights of edges

The difference in the volumes of interprovincial embodied energy trade will lead each edge to have an inconsistent impact. This paper takes the volume of interprovincial embodied energy trade as the weight of the connecting edges, i.e., f'^{ij} in Eq. (4). The cumulative distribution is used to describe the distributing characteristic of the weights of edges f'^{ij}. This is the probability distribution of the edges over the whole network. The cumulative distribution function is described in the following equation.

$$CP(w) = \sum_{W \geqslant w} p(W) \tag{9}$$

where $CP(w)$ is the cumulative distribution of edges whose weight is larger than w, $p(W) = N_W/N$ is defined to be the fraction of edges in the network with weight W, and N_W is the total embodied energy of edges with weight W. N is the total weight of edges in the whole network.

3.4.3. Community structure

In addition to knowing the underlying statistics of flows, we would like to know whether provinces cluster in any particular way. Such clusters are usually referred to as "communities" in the theory of complex network. It has been observed that many real networks exhibit a concentration of links within a special group of nodes called communities. The detection of community structure of a given network helps to discover some hidden features of its topological architecture. In this study, we adopted the well-known formulation of modularity maximization given in Blondel et al. [46]. Modularity is defined as:

$$Q = \frac{1}{2w} \sum_i \sum_j \left(w_{ij} - \frac{w_i w_j}{2w}\right) \delta(C_i, C_j) \tag{10}$$

where w_{ij} represents the weight of the edge between node i and j. w_i and w_j are the node strengths of node i and j respectively. C_i is the community to which node i is assigned, and C_j is the community to which node j is assigned. $\delta(C_i, C_j)$ is 1 if $C_i = C_j$ and 0 otherwise, and $w = \frac{1}{2}\sum_i \sum_j w_{ij}$.

The algorithm is divided into two phases. First, it assigns a different community to each node. For each node i, it considers its neighbors j and evaluates the gain of modularity ΔQ by placing i in the community j. The node i is then placed in the community for which ΔQ is

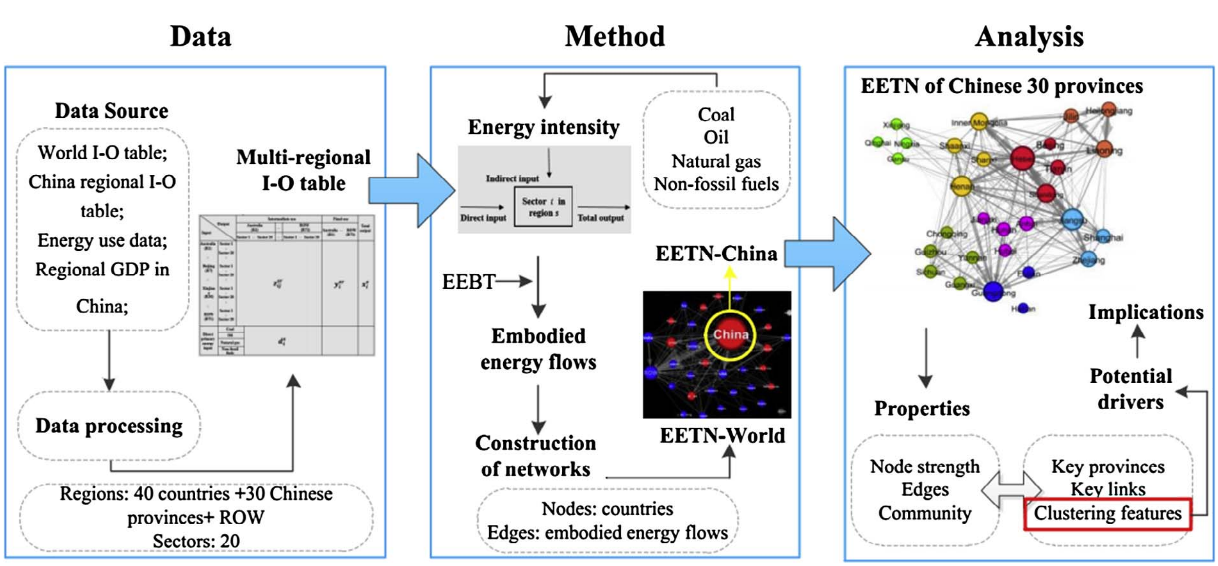

Fig. 2. The whole flow chart of the method with complex network analysis.

maximum, but only if ΔQ is positive. If no positive gain is possible, i stays in its original community. The gain of modularity ΔQ can be calculated by:

$$\Delta Q = \left[\frac{\sum_{in} + k_{i,in}}{2m} - \left(\frac{\sum_{tot} + k_i}{2m}\right)^2\right] - \left[\frac{\sum_{in}}{2m} - \left(\frac{\sum_{tot}}{2m}\right)^2 - \left(\frac{k_i}{2m}\right)^2\right] \tag{11}$$

where $\sum_{in}$ is the sum of the weights of the links inside a community C. $\sum_{tot}$ the sum of the weights of the links incident to nodes in C. k_i is the node strength of node i. $k_{i,in}$ is the sum of weights from node i to the nodes in C, and m is the sum of weights of all the links in the network.

This process is applied repeatedly and sequentially for all nodes until no further improvement can be achieved and the first phase is then complete. The second phase consists in building a new network whose nodes are the communities found during the first phase. The weights of the links are given by the sum of the weights of the links between the nodes in the corresponding two communities. Once the second phase is completed, the first phase is reapplied to the resulting network, and this process is iterated. The two phases are iterated until there are no more changes and the maximum modularity is attained. The number and size of the groups are thus determined by the network itself and not by the experimenter.

For finding communities, we set self-flow of regions to zero, since these flows may reduce the resolution of the method. Identifying clusters helps understand the potential impacts of region-specific policy intervention through supply chains.

4. Empirical results

4.1. Total primary energy embodiments

4.1.1. Position of China in the world

In 2009, the world total primary energy use embodied in interregional trade was 390,157 PJ, as shown in Table 2. In the primary energy embodiments, coal accounted for the largest percentage, approximately 43.5%, which is 2 to 3 times larger than the other three energy sources. The amounts of oil and natural gas embodied in interregional trade were basically the same, with non-fossil fuels being the lowest. For countries, the distribution of embodied energy imports and exports was unbalanced. China, Russia, Korea, and India were the top four net exporters, as shown in Fig. 3. China has the largest embodied energy exports in the world, which is three times larger than the USA (which has the largest embodied energy imports).

Moreover, a large amount of energy is embodied in exports, which is more than the energy embodied in imports. It indicates that China is a net exporter of energy. Because a lot of primary energy was used to produce products for exporting to other countries. The expanding total volume of exports and increasing exports of energy-intensive goods enlarged the energy embodied in exports. Thus, the energy embodied in international trade should receive special attentions in energy policies. The higher proportion of coal in total primary energy exports is consistent with the national energy situation.

Total energy use from domestic trade in China was 91,100 PJ, which accounted for approximately 23.3% of the world. For coal, China dominated the world with a percentage of almost 40%. This can be explained by China's coal-dominated energy and electricity generation structure. Because of the outstanding position of China, the ensuing sections mainly focus on the analysis of China's interprovincial energy transfers.

4.1.2. Key Chinese provinces based on node strength

The main problem is the identification of dominant provinces, which can be calculated by node strength. A province's out-strength (interregional export) explains how its production-based energy is embodied in the interregional trade to satisfy other regions' demands. A province's in-strength (interregional import) explains its consumption-based energy use embodied in interregional trade. Fig. 4 displays the distribution of both the interregional import and export of China's 30 provinces/municipalities in the year of 2009. In this paper, interregional trade includes interprovincial and international trades.

From Fig. 4, the top three importers of embodied energy were Guangdong, Jiangsu, and Hebei respectively. Guangdong and Jiangsu had substantial embodied energy inflows via interregional trade because both are major provinces in terms of manufacturing trade with strong economies. The development of manufacturing trade requires substantial inflows of energy and energy-intensive products from other regions in China or aboard due to deficient energy resources. They are China's economy-prosperous provinces, especially for Guangdong and Jiangsu, which are China's top two richest provinces. Developed regions, such as Beijing, Tianjin, and Shanghai, were found to be net importers. These three regions are also China's major ports.

The three provinces with the greatest outflows of embodied primary energy via interregional trade were Jiangsu, Shandong and Hebei. The energy-intensive sectors occupy a large proportion of these provinces' industrial structures, and the energy-intensive products are the major products traded. Inner Mongolia and Henan also have high outflows of embodied primary energy via interregional trade because they are China's major sites of energy production. In 2009, the four provinces with the smallest outflows of embodied primary energy via interregional trade were Hainan, Qinghai, Ningxia and Gansu. These provinces are not major energy producers. Moreover, they are economically underdeveloped regions. Their low level of industrial development results in less outflow of energy embodied in interregional trade products. As one of China's top three richest provinces, Shandong was found to be a net exporter. Meanwhile, resource-oriented areas including Shanxi, Inner Mongolia, Liaoning, and Henan provinces are also important net exporters of embodied coal energy.

In relation to the energy categories, coal accounted for the largest proportion, owing to China's particular energy structure. The energy structure of China is gradually developing into a comprehensive and diverse system but is still be dominated by coal resources [47].

4.1.3. Cumulative distribution of weights of edges

In addition to the key provinces, we also analyzed the links that carry embodied energy flow, and thus determined a threshold is needed, since all sectors consume energy more or less, typically with more than 90% of all possible flows having non-zero weights. Therefore, the EETN established is an entirely connected network. However, the weight of each link is quite different. Thus, a distribution analysis of the weights of edges is needed, as shown in Fig. 5. This clearly shows that less than 50% of edges carry approximately 90% of the total embodied energy, which calls for further investigation. The feature of heterogeneity is observed from the distribution of the four types of energy categories. In order to obtain a more accurate community detection, we further constructed a threshold network in which only the larger edges containing 90% of embodied energy are considered, with the edges smaller than the threshold being ignored.

Table 2
Total primary energy embodied in trade for China and the world, 2009.

	World (PJ)	China (Total domestic interprovincial trade, %)
Coal	169,761	38.9%
Oil	83,077	12.6%
Natural gas	75,410	6.9%
Non-fossil fuels	61,907	15.1%
Total primary energy	390,157	23.3%

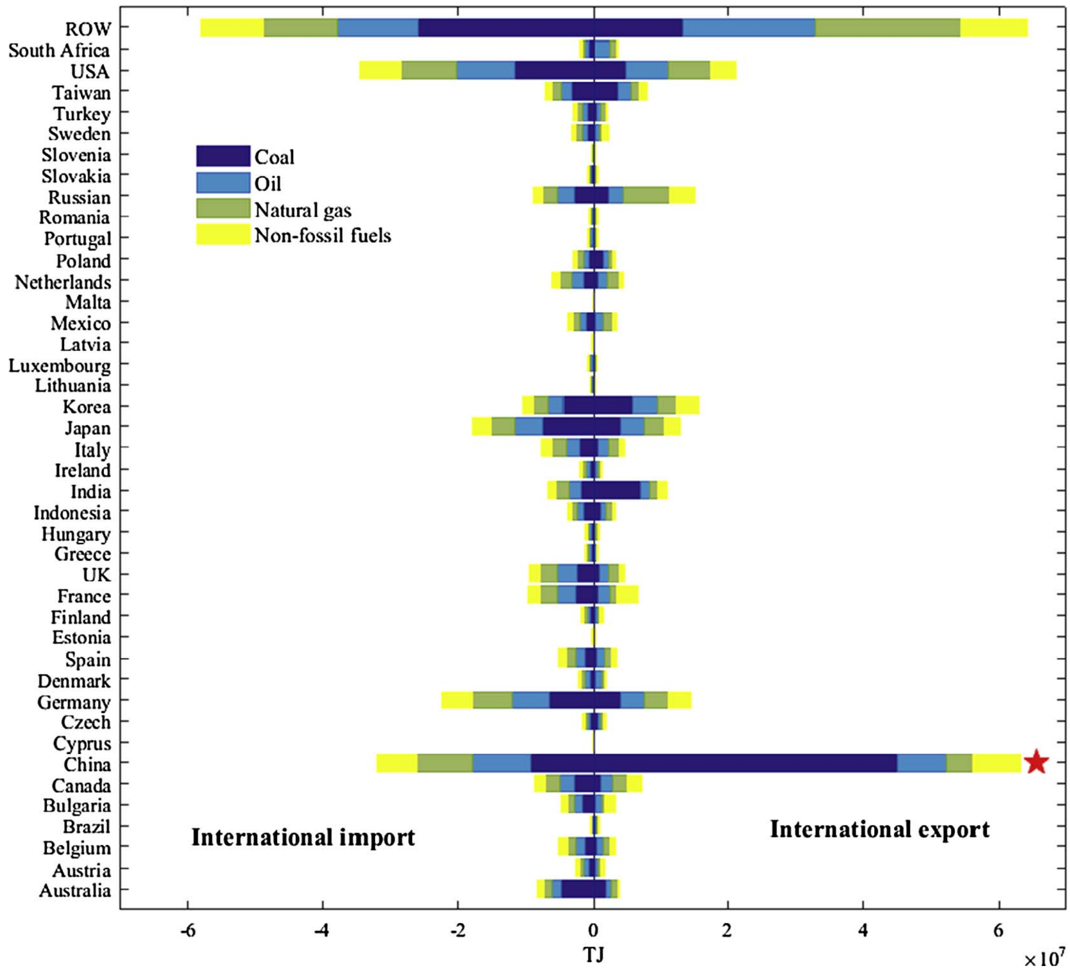

Fig. 3. National distribution of world's embodied energy trade by fuel.

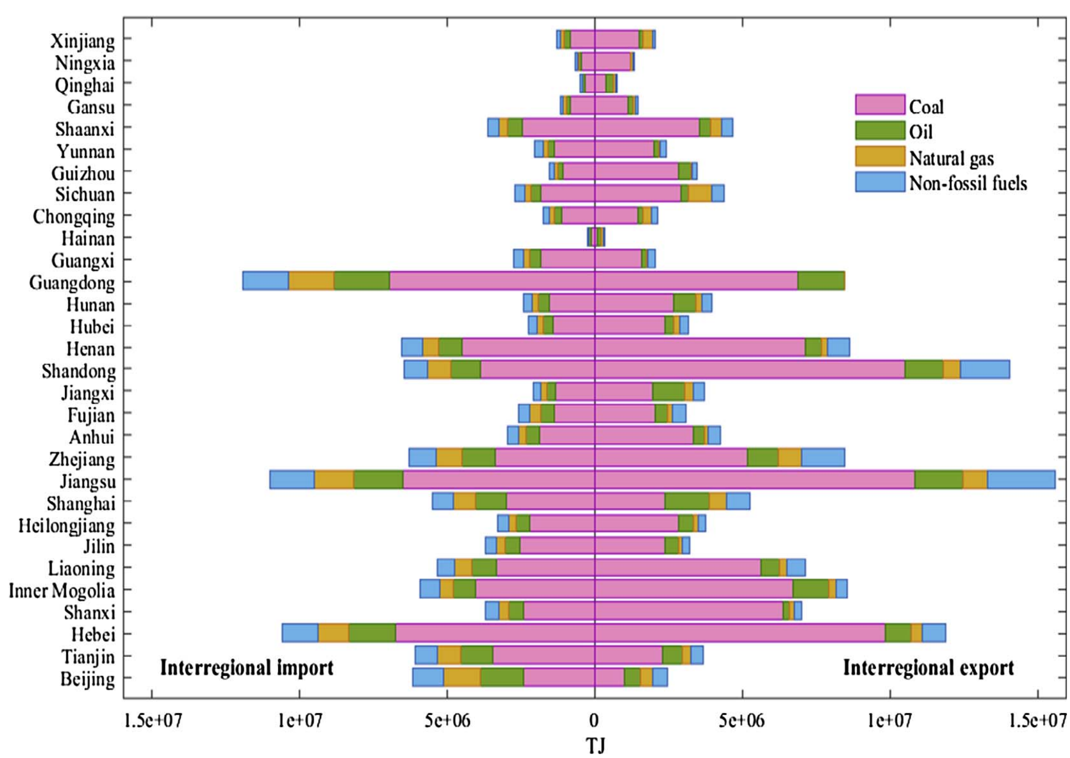

Fig. 4. Provincial distribution of China's embodied energy trade by fuel.

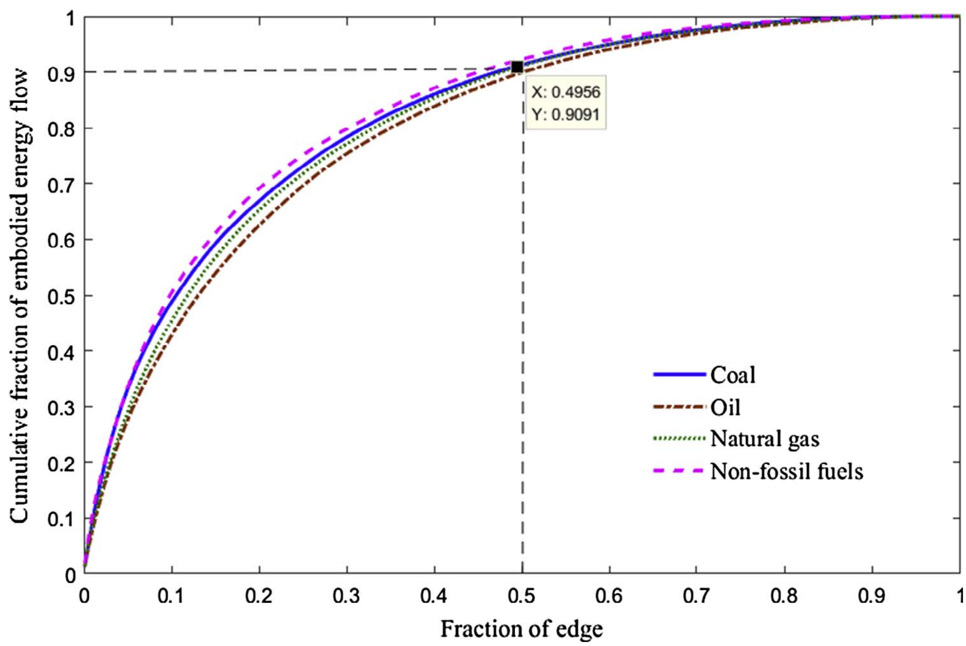

Fig. 5. Scatter of the cumulative fraction of edges by weight by fuel in EETN.

Table 3
The eight regions of China used in this study and their constituents.

Region	Abbreviation	Province/municipality
Northeast	NE	Heilongjiang, Jilin, Liaoning
North Coast	NC	Beijing, Tianjin, Hebei, Shandong
East Coast	EC	Jiangsu, Shanghai, Zhejiang
South Coast	SC	Guangdong, Fujian, Hainan
Middle Reaches of the Yellow River	MYE	Shaanxi, Henan, Shanxi, Inner Mongolia
Middle Reaches of the Yangtze River	MYA	Hunan, Hubei, Jiangxi, Anhui
Northwest	NW	Gansu, Qinghai, Ningxia, Xinjiang
Southwest	SW	Guangxi, Yunnan, Guizhou, Sichuan, Chongqing

4.2. Clustering analysis of China's interprovincial embodied energy in trade

In addition to the importance of individual provinces and links, it is also useful to identify the clusters of the provinces that can potentially control energy use collectively under the influence of the same or similar policy interventions. Provinces in the same cluster tend to have stronger relationships with one another than with provinces outside the cluster. Furthermore, the provinces in the same cluster may not necessarily belong to the same geographical region. Thus, we further divided the Chinese economy into eight aggregated regions; the constituent of each aggregated region is shown in Table 3.[2]

The results of community structure, calculated by the clustering algorithm given in Section 3.4, are shown in Figs. 6 and 7, where the size of nodes is described in two different ways, namely production-based and consumption-based energy. The color of the inner nodes denotes the eight regions as shown in Table 3. The main intention is to provide a comprehensive description of the possible influences on the formation of clusters. The dashed circle indicates the provinces that belong to the same sub-cluster, while the line's thickness depicts the amount of embodied energy. Not all links are shown because the threshold being considered rendered them not being influential.

4.2.1. EETN of coal

The network of coal is dominated by four clusters including the Jing-Jin-Ji Area, Yangtze River Delta, Pearl River Delta, and NE respectively (see Fig. 6(a) and 7(a)). These are also China's special economic zones. Hence, the community structure of the coal network directly reflects the influence of the economy due to China's special energy structure. In 2009, coal consumption occupied 70.4% of China's energy consumption mix, especially for the industries of "Electricity, Gas, and Water supply (S16)", "Basic Metals and Fabricated Metal (S11)" and "Chemical Industry (S9)". Therefore, China's generation mix should be shifting towards less coal and more other sources of energy (such as natural gas, hydro, and other renewables). Moreover, the provinces in the same cluster tend to be geographic neighbors.

We also observed that the largest community (Cluster 1), consisting of NC, MYE, and NW, accounted for 79.13% of China's total coal reserves and 62% of interprovincial coal consumption. For the provinces in Cluster 1, Shandong belongs to NC and has an agglomeration of manufacturing industries. The strong energy demand in neighboring provinces creates favorable conditions for Inner Mongolia joining the Jing-Jin-Ji area, owing to Inner Mongolia's considerable lignite resources as well as the capacity to meet the demand for heating and power for a long time. The energy and chemical industries are the pillars of Shaanxi. In 2009, Shaanxi had coal reserves of approximately 105.55 billion tons, with a diversified and complementary industry structure including coal mining, chemical industry, and coal-fired power generation. In addition, Xinjiang is also rich in coal resources and Yili Basin has coal reserves of approximately 55.8 billion tons. This provides a protection for the development of the coal chemical industry and to distribute a large amount of electricity from the coal-rich northwestern part of Xinjiang to other regions in China where energy is scarce. Therefore, the coexistence of the producing, consuming, and processing regions in the same cluster attests to the existence of a comprehensive industrial circle.

Additionally, Anhui province (Cluster 3) belongs to the MYA, but has a stronger relationship with provinces in EC, which reflects cross-regional industrial transfer. In January 2010, the State Council formally approved

[2] We follow the provincial names given in the original data source (http://data.stats.gov.cn/english/). Mainland China consists of 30 provinces/ municipalities, which has been conventionally divided into eight regions by the Development Research Center of the State Council of the People's Republic of China (DRC) [48]. Su and Ang [43] and Zhang et al. [26], for example, have studied the problems of energy and environments from the perspective of the eight regions.

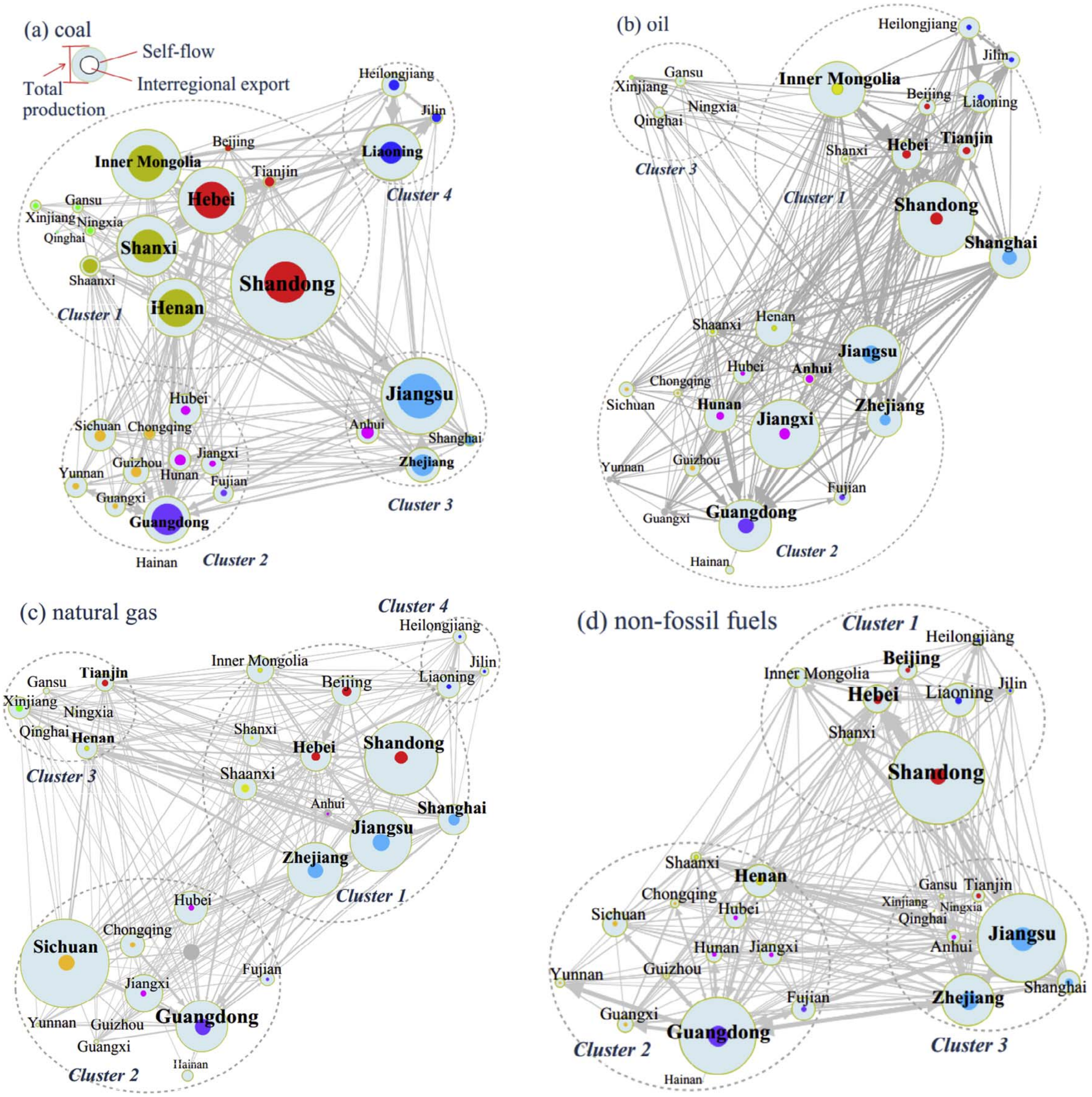

Fig. 6. The clusters based on production and interprovincial export, 2009. *Notes*: the size of the outer circle represents provincial energy production; the size of the inner circle represents interregional exports. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the *"Wanjiang city belt to undertake industrial transfer demonstration area planning"* because of Anhui province's advantages in natural and labor resources. In Cluster 2, provinces including Guizhou, Yunnan, and Sichuan, are also rich in coal resources. Guangdong has the largest coal imports, owing to the diversified trade structure in Pearl River Delta Region. In Cluster 4, the three NE provinces are the traditional industrial bases in China, with rich mineral resources, a strong industrial base, and superior agricultural conditions. Thus, a stronger sub-group is formed of the industries of "Chemistry Industry (S9)" and "Basic Metals and Fabricated Metal (S11)". The characteristics of regionalism and a comprehensive industrial circle are also verified by this sub-group.

4.2.2. EETN of oil

The community structure of the oil network is characterized by three sub-groups. First, Cluster 1, consisting of NC, MYE, NW, and Shanghai, accounted for 52.2% of China's oil reserves and 48% (9,192PJ) of interprovincial oil consumption respectively. Shanghai has a strong relationship with Northern China; this is because Shanghai has the largest petrochemical and chemical integration enterprises in China. It is also an important region China for producing refined oil, intermediate petrochemical products, synthetic resin, and synthetic fiber. This enables Shanghai to have larger embodied oil imports from resource districts as well as larger embodied oil exports. Daqing oilfield, being China's largest oil base, is the NE industrial pillar, producing the bulk (approximately 40%) of China's oil. Thus, the feature of a comprehensive industrial circle is also displayed in this cluster – for instance, the abundant oil reserves in NE China's largest refining-chemical integrated enterprise in Shanghai and deep-processing industries in Inner Mongolia. This result is consistent with the study of the coal network. However, the economic factor is limited to the scaling pattern of the community structure for the oil network.

Secondly, the marked changes in Cluster 2 compared with the coal network, are associated with the Jiangsu and Zhejiang provinces. The oil imports in Jiangsu and Zhejiang were driven by the double shift strategy in Guangdong, resulting in stronger relationships between these three provinces, mainly involved in "Electrical and Optical Equipment (S13)", "Chemistry Industry (S9)" and "Electricity, Gas and Water Supply (S16)".

Lastly, Cluster 3 is constituted by four NW provinces of Xinjiang, Gansu, Qinghai, and Ningxia. The oil reserves in Cluster 3 accounted for

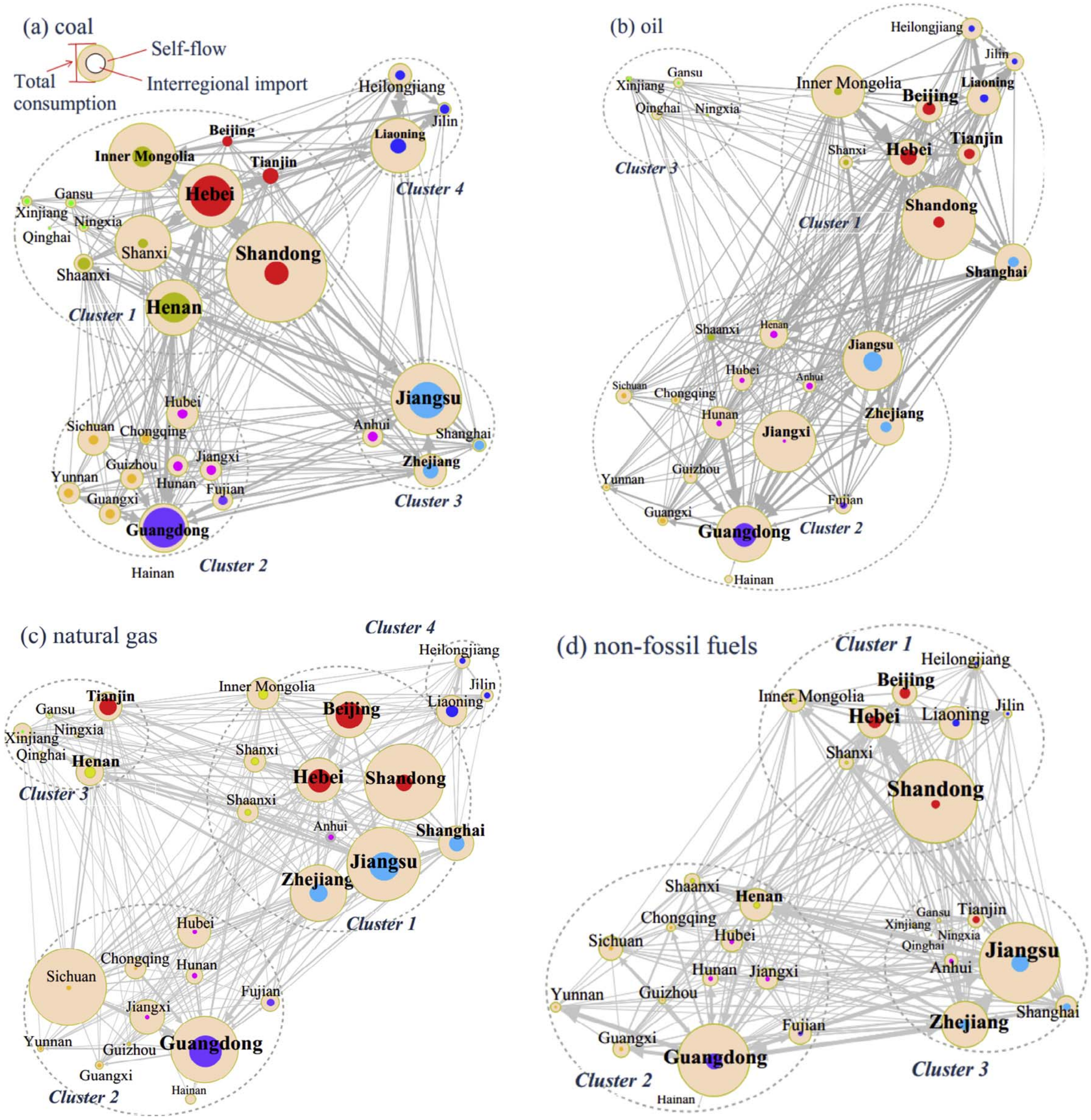

Fig. 7. The clusters based on consumption and interprovincial import, 2009. *Notes*: the size of the outer circle represents provincial energy consumption; the size of the inner circle represents interregional imports. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

23% of all China. The largest was Xinjiang, which accounted for 70% of the NW. Moreover, embodied oil consumption accounted for only 3%, resulting in only a weak geographic and economic influence.

4.2.3. EETN of natural gas

The community structure of the natural gas network shows that infrastructure is an important driver, which is significantly different from the above two networks. Cluster 1 had the largest interregional natural gas absorption, accounting for 55% of all China. Natural gas reserves in this cluster accounted for 35.8%, including the Inner Mongolia and Shaanxi provinces; Jiangsu, Hebei, and Beijing are also major consumers.

Interestingly, Henan and Tianjin imported a large amount of natural gas from Xinjiang through the West-East Gas Pipeline and the Shaanxi-Beijing Pipeline System and are mainly involved in the “Basic Metals and Fabricated Metal (S11)” and “Chemistry Industry (S9)” sectors. Ultimately, a comprehensive industrial cycle will be formed owing to the largest natural gas reserves in Xinjiang, the natural gas cogeneration advantages of Tianjin, and the resource and location conditions in Henan. This depends on China’s natural gas transmission and distribution market structure, i.e., the distribution of the long-distance pipeline, regional pipeline network, etc. (see Fig. A1).

The distribution of China’s gas pipelines and liquefied natural gas (LNG) terminals is shown in Fig. A1. Cluster 1 also shows the importance of the combination of the LNG terminals and the domestic pipeline network. In June 2004, China proposed a LNG terminal project to build a number of terminals to accept LNG transmission in Guangdong, Fujian, Shandong, Zhejiang, and Jiangsu. The LNG terminals play a key role in promoting international trade and the storage and distribution of domestic gas, thereby providing a better protection strategy and diversified supply structure for China.

4.2.4. EETN of non-fossil fuels

In the community structure of non-fossil fuels network, all 30 regions were divided into three clusters according to their linkages, which are mainly due to their developed economy and advanced production technology. There is a considerable amount of production and consumption in these three sub-groups; compared with regionalism, the impact of the resource factor is more prominent.

From the perspective of renewables, Cluster 3 is China’s renewable energy development base, as exemplified by the photovoltaic power

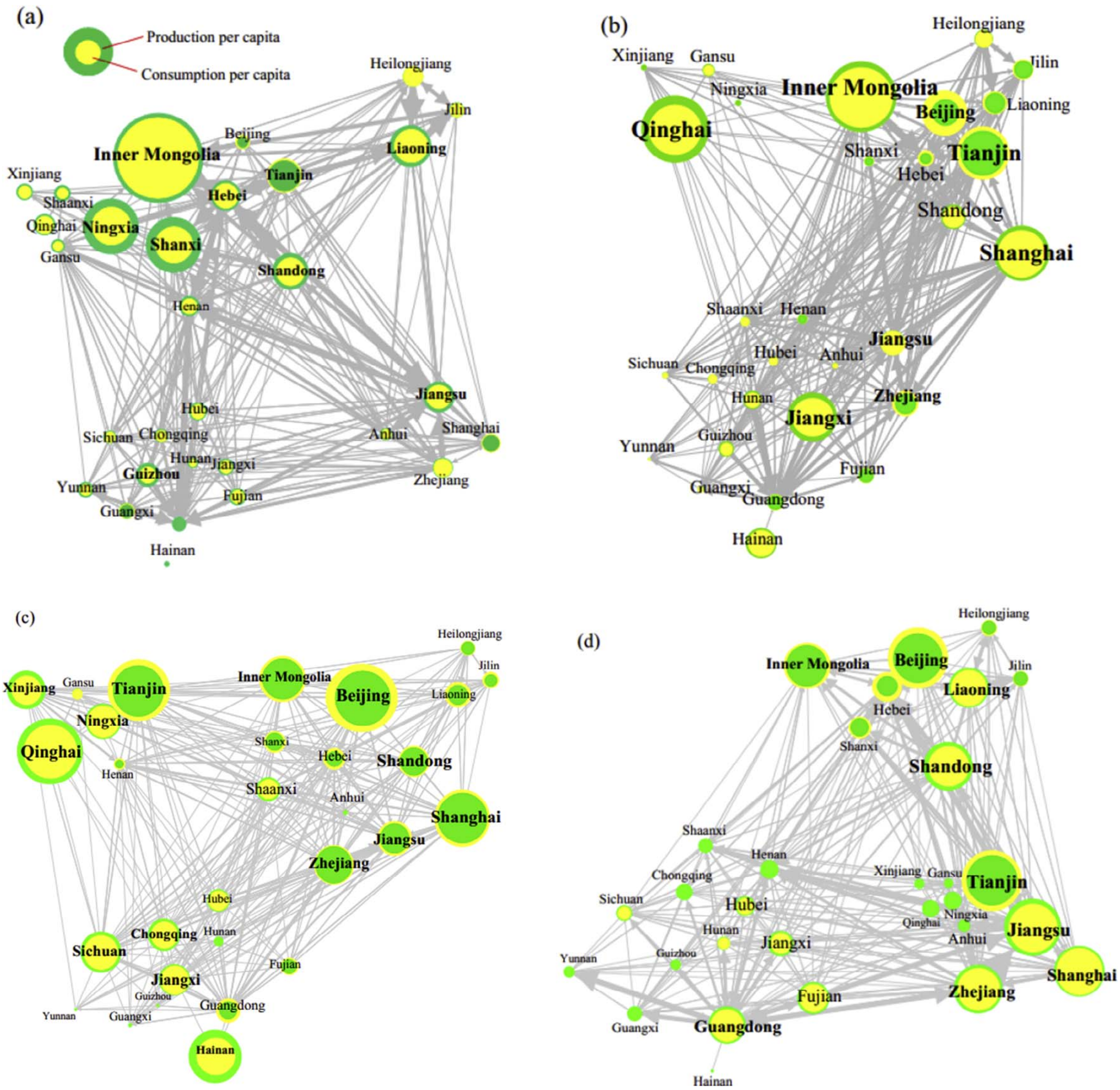

Fig. 8. Both production-based and consumption-based energy embodiments per capita. *Note:* (a) Coal; (b) Oil; (c) Natural gas; (d) Non-fossil fuels. The solid green circle in represents energy production per capita while the solid yellow circle denotes is energy consumption per capita. In this case, the energy consumption of a province includes interregional consumption (the data in Fig. 4) and local energy use. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

generation in Jiangsu. Compared with the fossil fuel networks, Xinjiang has strengthened its links with EC areas. This shows that the resource advantages of Xinjiang are being transformed into economic advantages through the bundling of wind and solar power, with fossil fuels governed by the "West to East Power Transmission Project". In addition, Inner Mongolia has abundant wind resources and accounts for more than 50% of China's land wind energy resources. In spite of superior grid facilities, location and policy advantages, Inner Mongolia also has a strong relationship with adjacent NE and NC areas. Therefore, China should strengthen its technological innovation capacity and R&D investment to establish a more competitive industrial chain to promote the inter-regional consumption of renewables. Hydro accounted for a large proportion in the structure of new and renewable energy, being mainly focused in South China (see Figs. A2 and A3). This verifies the consistency of regionalism and resources. In all, however, the indications are that inter-district renewable consumption was insufficient.

4.3. Implications for provincial energy consumption

4.3.1. Analysis of energy consumption per capita

Total energy production and consumption per capita for selected 30 regions, which is defined as the sum of self-flow and export/import (interregional and international) divided by the population, is shown in Fig. 8. The solid green circle represents energy production per capita, while the yellow color denotes provincial energy consumption per capita. If a region's energy consumption per capita is larger than production, the green circle will be inside the yellow circle.

Inner Mongolia has the highest total coal production and consumption per capita. This is because the population of the resource-oriented province of Inner Mongolia occupied less than 19% of the total population of China, which is far below the regional average value. Inner Mongolia was three times larger than that of Hebei province, which had an equivalent amount of coal production and consumption. Other important provinces such as Shanxi, Ningxia, and Liaoning were higher than some developed regions and the country's average level. Generally, all regions have higher coal production per capita than consumption, except for Beijing, Tianjin, and Shanghai. The distribution of coal production and consumption per capita shows that significant differences existed between resource-orientated areas and developed regions.

For oil, there were obvious differences between North and South areas, while natural gas had obvious difference between East and West China. The non-fossil fuel network was different for the Eastern coastal area in terms of the amount of energy production and consumption. The oil consumption for Qinghai is comparable to such developed regions as

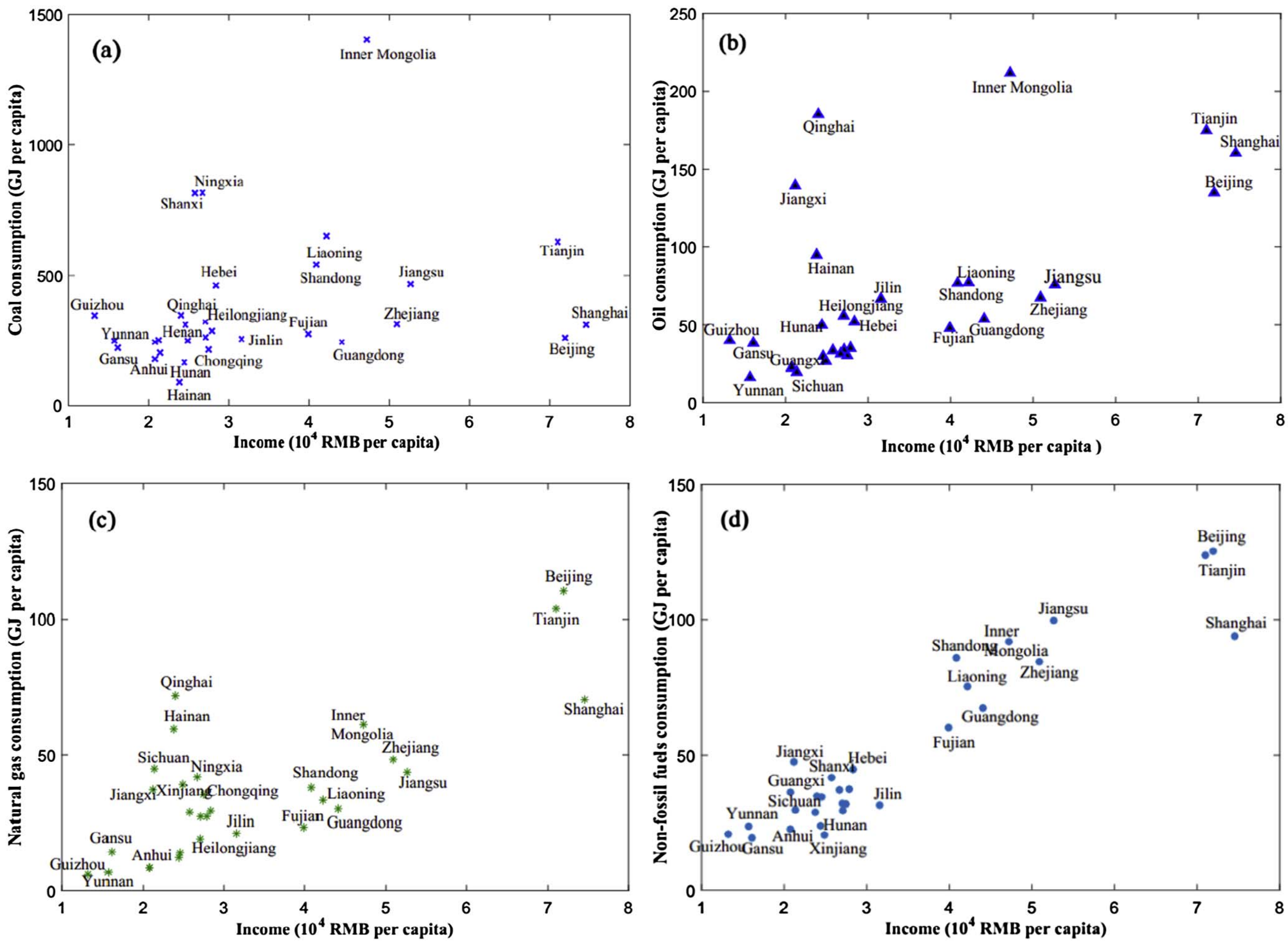

Fig. 9. Primary energy consumption vs. GDP per capita.

Tianjin and Shanghai. Frequent foreign trade in Beijing, Tianjin, Shanghai, and Guangdong has led to a large amount of imported goods, resulting in larger energy consumption than production.

China's regional differences in energy consumption per capita are largely due to economic development. Energy consumption has played a significant role in promoting the economic development of provinces in China, especially dominating development in the first and second industry. Heavy industries, which account for a large proportion of the secondary industry, depend heavily on energy, because of it being inseparable from economic growth. These results above give us the grounds to further analyze the relationship between energy consumption and economic development.

4.3.2. The nexus of economic growth and energy consumption

Further analysis of embodied energy consumption per capita in each province reveals that the characteristic of Environmental Kuznets Curve (EKC) hypothesis do not exist. The EKC hypothesis postulates an inverted U-shaped relationship between the level of environmental degradation and income growth [49] – i.e., environmental degradation increases with per capita income during the early stages of economic growth, and then declines with per capita income after arriving at a threshold. Can economic growth have a positive impact on energy consumption? The relationship between primary energy consumption (per capita) and income (per capita) is described in Fig. 9.

As one of the elements of production, energy investment generally promotes economic growth, which in turn further increases energy consumption. This is basically the consistent trend between these two factors. The results in Fig. 9 fail to support the validity of the EKC hypothesis in Chinese provinces. Overall, provinces with high energy consumption per capita are concentrated in developed provinces, whereas the less energy-intensive regions are located in the undeveloped provinces for the other three energy sources except for coal. For coal, there are no distinct differences between China's 30 regions because of the dominant status of coal in China, development of associated technologies, provincial industrial transfer mechanism, and provincial economy as well as openness.

Although higher energy-saving targets were put forward during the 11th Five-Year period (see Table A2), the energy consumption in such provinces as Inner Mongolia, Shanxi, and Ningxia is still high. The reason lies in the industrial structure. In 2009, the industrial added value of Inner Mongolia, Shanxi, and Ningxia accounted for 46.23%, 47.82%, and 38.45% of their GDP respectively. Industry is the most important energy-consuming sector in China. During the 11th Five-Year Plan period, Inner Mongolia was at an important stage of accelerating the development of a new type of industrialization. A single and heavily weighted industrial structure is less adaptable to cyclical fluctuations in the economy.

Non-fossil fuel consumption tends to rise monotonically as income grows – i.e., there is no EKC-pattern with respect to non-fossil fuels. An explanation is that the developed regions have paid more attention to the development of renewable energy to meet their energy and economic sustainable development. For example, Shanghai has launched a number of renewable energy projects in industrial parks, actively developed distributed energy supply, and vigorously promoted distributed energy supply systems in new municipal hospitals during the 11th Five-Year Plan period. Therefore, the level of economic development and policy guidance are the main factors behind non-fossil energy

consumption. In short, per capita income level has a positive effect on non-fossil fuel energy use.

5. Discussion and implications

According to the essential roles played by the provinces in the EETN, well-focused policies could be implemented accordingly. Based on the node strength measures in the complex network, these strong provinces are recognized as hub provinces in EETN and key drivers of embodied energy flow. Energy-related policies targeting these hub provinces will therefore dramatically promote the performance of China's embodied energy flow network – most likely improving the efficiency of policy implementation.

The heterogeneous distribution of the weights of edges indicates that half the connections are peripheral in the EETN. However, the scale-free characteristic is weak compared with traditional scale-free networks. Therefore, simply stabilizing the hub connections is insufficient. More connections and the cooperation of related provinces becomes the key to maintaining the effective operation of the whole energy flow system.

At China's provincial scale, a community represents a group of provinces that affect one another's energy consumption more critically than provinces outside the community. Therefore, detecting communities helps understand the potential impact of policy intervention, given that spillover effects of the policy in one region can be more effectively transferred through the close connections among regions in the same communities. The close relationships between provinces in the same community call for greater cooperation. The judicious choice of joint energy-saving provinces according to communities will greatly help the spread and diffusion of effects. Moreover, because the number of provinces and their locations are related to the time and effect of national policy, the sub-group provides a reference for all provinces to choose their cooperators as well as policymaking.

Accurately grasping the relationship between the economy and different types of energy flows between regions is conducive to the formulation of economic and environmental policies. For example, Anhui province has undertaken the production activities of developed regions along its Eastern Coast to some extent. These developed regions should provide compensation and technology transfer for Anhui to improve its clean production capacity. However, the policies for different resources depend on various factors. Resource endowment and economic development level are the most important drivers of provincial coal consumption. The formation of interprovincial oil flow highlights the influence of industrial transfer while the economy becomes weaker. Pipelines and LNG receivers are the driving forces for the formation of communities in the natural gas network. As for non-fossil fuels, the limiting factor lies in resources and policy. China can improve subsidy policies in terms of targets, quotas, and forms, based on the connections and communities to promote the development of renewable energy.

At present, pollution control policies related to production activities are given special attention. However, resource-poor provinces have to import more energy from other provinces in China or abroad due to the limited indigenous energy resources. High energy production levels in resource-rich provinces are driven by interregional energy trade; therefore, it is necessary for provinces from a comprehensive industrial circle to make adjustments by tracking energy use along whole supply chains. Meanwhile, it would be beneficial for the government to pay to more attention ecological compensation in practice, because some provinces have undertaken more energy consumption and environmental pollution to meet the consumption of other provinces. From a decision-making perspective, energy and environmental policies are inextricably linked. Energy-related policies combined with industrial, environmental, and international policies can realize the potential for mutually reinforcing policies.

6. Conclusions and future prospects

We constructed a network model by combining the EEBT approach and complex network analysis. This model is an extension of the general EEBT approach. The results obtained at the provincial level can help provincial energy policy making in a large country such as China. Coal occupies the largest proportion of the primary energy embodiments of China's energy structure. The empirical study also shows that the developed provinces of Hebei, Jiangsu, Shandong, and Guangdong are generally top importers and exporters, while developed municipalities including Beijing, Tianjin, and Shanghai are net importers of embodied primary energy from interregional bilateral trade.

The provincial embodied primary energy analysis provides more information than traditional input-output analysis by taking into account the community structure together with provincial linkages. The results revealed in the clusters are valuable, and supplement the understanding of the underlying drivers of different interprovincial energy flows. It also helps to provide critical insights into China's current end-reduction-oriented energy policies by addressing the problems of regional responsibility transfer.

In particular, the driving forces are quite different between the various energy sources, except for the consistent characteristics of comprehensive industrial circles and regionalism. The economic mechanism was identified by the community structure of embodied coal network. Cross-regional industrial transfer is an important influencing factor in the formation of embodied coal and oil networks. There is also the need for governments to understand not only the importance of regional restructuring, but also the infrastructure in China's interprovincial trade of embodied natural gas. Using the data for China's gas pipeline network and LNG terminals, we showed that infrastructure affects clusters of provinces, tying them together by interprovincial trade.

The problem cannot be easily resolved, but a better understanding is useful in the debate over national energy conservation and emission reduction. The framework used in our analysis is generic and it can be equally applied to similar such cases, as the network model proposed is not limited to just analyzing China's interprovincial embodied primary energy flow. With trade becoming increasingly important in energy/emission accounting, the proposed models are useful for analyzing embodied energy flows at the global/national/regional/industrial levels, and exploring the changes of underlying drivers from a system perspective when the data is updated.

Further improvements to our study can be made in the interdependent network; one challenge, for instance, is to quantify the weights of interlayer edges. In practice, the interactional relationships that exist between multilayer energy networks are due to their substitutions.

Acknowledgements

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Appendix A

See Table A1 and A2 and Figs. A1–A3.

Table A1
Sector information for the multi-regional input-output table.

Code	Sector category	Code	Sector category
S1	Agriculture, Hunting, Forestry and Fishing	S11	Basic Metals and Fabricated Metal
S2	Mining and Quarry	S12	Machinery, Nec
S3	Food, Beverages and Tobacco	S13	Electrical and Optical Equipment
S4	Textiles and Textile Products	S14	Transportation Equipment
S5	Leather, Leather and Footwear	S15	Other Manufacturing
S6	Wood and Products of Wood and Cork	S16	Electricity, Gas and Water Supply
S7	Pulp, Paper, Printing and Publishing	S17	Construction
S8	Coke, Refined Petroleum and Nuclear Fuel	S18	Transportation and warehousing
S9	Chemical Industry	S19	Wholesale and retail trade
S10	Other Non-Metallic Mineral	S20	Other Services

Table A2
Energy consumption reduction per unit of GDP in the 11th Five-Year Plan period (2006–2010).

Provinces/Municipalities	Energy consumption reduction per unit of GDP (%)
Shanxi, Inner Mongolia, Jilin, Shandong	22%
Beijing, Tianjin, Hebei, Liaoning, Heilongjiang, Shanghai, Jiangsu, Zhejiang, Anhui, Jiangxi, Henan, Hubei, Hunan, Chongqing, Sichuan, Guizhou, Ningxia, Shaanxi, Gansu	20%
Yunnan, Qinghai	17%
Fujian, Guangdong	16%
Guangxi	15%
Hainan	12%

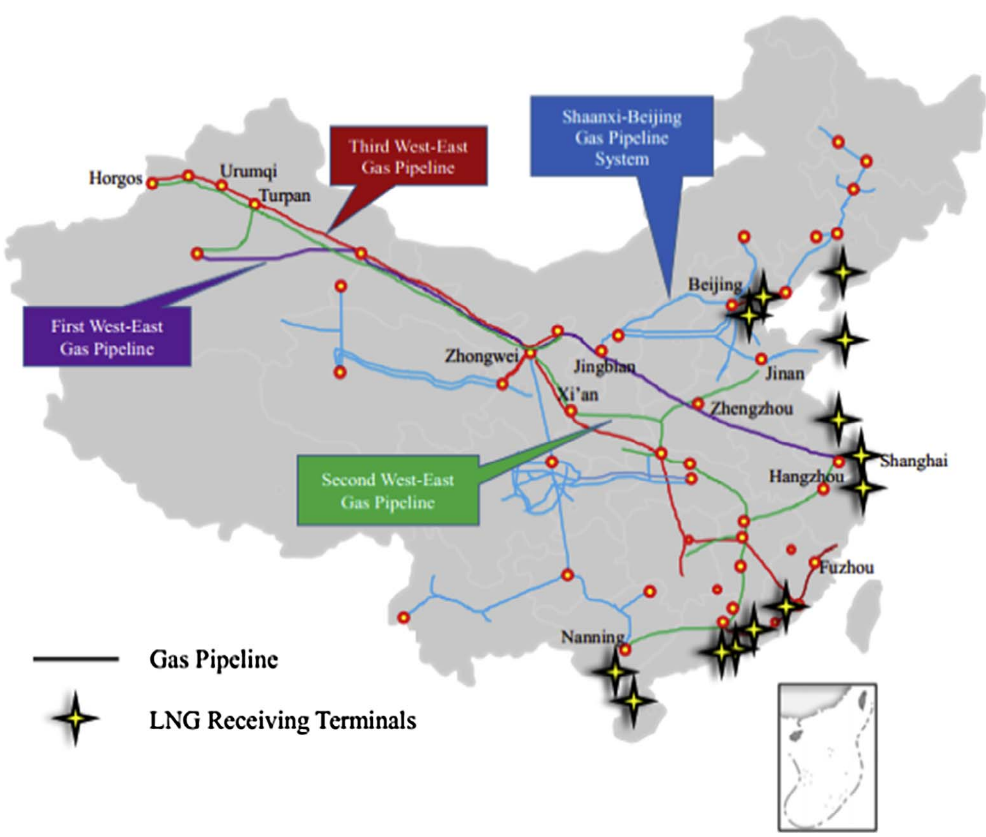

Fig. A1. Road map of China's gas pipeline and LNG receiving terminals by end of 2013.
Source: redrawn by the authors according to information from Refs [50,51].

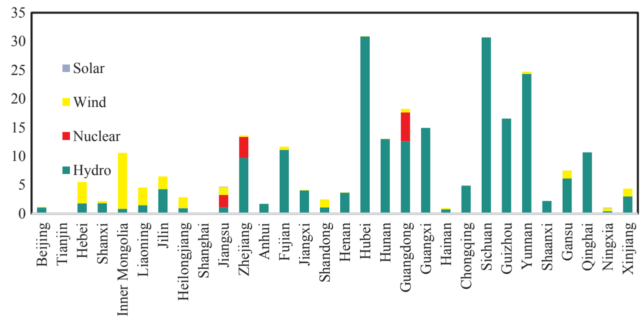

Fig. A2. China's regional installed capacity of non-fossil fuels, 2010 (unit in million KW).
Source: redrawn by the authors according to data from the "Handbook of Brief Energy Data 2016" [52].

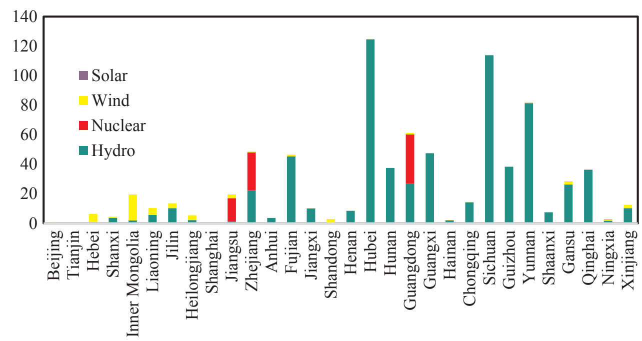

Fig. A3. China's regional generation of non-fossil fuels, 2010 (unit in billion kWh).
Source: redrawn by the authors according to data from the "Handbook of Brief Energy Data 2016" [52].

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